SWIRL FORMATION: COMETARY WIND OR METEOROID SWARM ENCOUNTER? L. V. Starukhina and Yu. G. Shkuratov, Astronomical Institute of Kharkov University, Sumskaya 35, Kharkov, 61022. Ukraine, starukhina@astron.kharkov.ua

Introduction: Cometary encounter with the lunar surface was proposed [1] and actively developed [2, 3] as a mechanism of swirl formation. In particular, the assumed low maturity of the swirl regolith was supposed to be due to interaction of the regolith with dust and gas components of cometary comas. However, the scenarios of such an interaction were limited to qualitative descriptions. A step to quantitative analysis of different cometary effects was taken in [4] where regolith processing by cometary debris was shown to be the most important for swirl formation.

Estimating cometary effects: Here we consider three effects that accompany cometary encounter with an atmosphereless body: (1) interaction of cometary gas with regolith, (2) plowing of regolith by meteoroid stream, and (3) interparticle collisions in ejecta.

(1) Interaction of cometary gas coma with regolith. The energy fluxes transferred by the passage of cometary coma can be shown to be enough for ablation of a the upper layers of regolith particles. However, cooling times for melted particle rims are too short (<<1 s) for the kinetic effects [5] that could provide relatively high brightness typical of swirls. Besides, thermal effect of the cometary nucleus (heating of the upper regolith layers in expansion of the impact vapor) is much stronger and will destroy the traces of coma passage. Volume concentration n_v of expanding impact vapor at a distance r from the explosion of a projectile with diameter D_p is about $n_v \sim (n_0/4)(D_p/r)^3$, $n_0 = 10^{23}$ cm^{-3} being volume concentration of solid material. n_v decreases to maximum 10^{13} cm^{-3} of coma densities n_c only at the distances $r \approx 10^3 D_p$, whereas n_c decreases by a factor of 100 at $r = 5D_p$. All density dependent parameters of the expanding impact vapor (pressure, energy density, energy flux) exceed those of cometary coma by a few orders of magnitude during about the same time intervals.

Mechanical effects of cometary coma (such as removal of a part of dust) are also negligible, because the dynamical pressure p_c of the cometary "wind" caused by coma passage is too small to overcome the interparticle adhesion. The pressure is $p_c = n_c m v^2$, where m is molecular mass, and v is the comet velocity. Taking $m = 3\cdot10^{-23}$ g and $v = 2\cdot10^6$ cm/s, for the most dense parts of coma obtain $p_c \approx 10^3$ dyn/cm^2, which is much smaller than the strength $\sigma \approx 10^6$ dyn/cm^2 of lunar soil provided by interparticle adhesion. Direct comparison of the forces from the coma wind upon the individual particles and interparticle capillary forces [6] gives the same ratio. Besides, $n_c \sim 1/r^2$, i. e., rapidly decreases with the distance r from the center of comet nucleus, so it acts during short times $\tau_c \approx D_p/v$ while $r \approx D_p$. Penetration of the coma gas into regolith cannot affect it either; pressure of the impact vapor seeped into the regolith is much higher (see above).

Coma "wind" is also insufficient to affect the ejecta of the small craters made in regolith by cometary dust. Since the acceleration caused by the wind pressure is inverse proportional to particle size l ($dv_e/dt \approx p_c/\rho l$, ρ being particle density), size separation of the ejecta particles could be expected. However, though the acceleration is high (up to $\sim10^5$ cm/s^2), it acts during time too small ($\tau_c \sim 0.01 - 0.1$ s) to increase the ejecta velocity v_e above the typical values for small craters (from $v_e \sim 10^3$ cm/s^2 for most ejecta to escape velocities for small part of them). Velocity increment in the direction of the wind is $\Delta v_e \approx 10^4$ cm/s for 10 μm and 10^3 cm/s for 100 μm particles, so, if the comet fall at a small angle to the lunar surface, separation distance for these particles is up to $v_e\cdot(\Delta v_e)_{max}/g \approx$ 1 km, which is much smaller than swirl length.

(2) Plowing of regolith by meteoroid stream. Another approach is to suggest that the comet nucleus is destroyed and estimate the effect of an encounter of remnants of a sungrazing comet with the Moon. The width of a meteoroid swarm formed after evaporation of volatiles and destruction of comet nucleus is much larger than the Moon size, so we assume the swarm to be rather dense or to have dense parts, which can take place shortly after comet decay. We suggest that such lunar structures as Reiner-γ could be formed by a dense shower of dust and stones of the sizes too small to produce observable craters and large enough to excavate immature regolith on the lunar surface. Such a shower can plow up large lunar areas and bring fresh material on the surface without traces of an impact.

Let us estimate the characteristics of a meteoroid swarm to provide the above described effect for Reiner-γ. Its total area can be estimated as $S = 300\text{x}10$ km^2. For the average plow depth $H = 1$ cm, the minimal total volume of the ejected material is $V = HS = 3\cdot10^{13}$ cm^3. Assuming 1/3 of the crater volume to be due to ejection and taking the ratio of crater to projectile volume $r_V = 3.1\cdot10^{-10}\rho v^2$ [7], where ρ is the projectile density in g/cm^3 and v is its velocity in cm/s, at $\rho = 3$g/cm^3 and $v = 2\cdot10^6$ cm/s, obtain $V_p \approx 3V/r_V \approx 2.4\cdot10^{10}$ cm^3 for the sum of projectile volumes and $7.2\cdot10^{10}$ g for the total mass, the diameter of a single body of this volume being $D_p \approx 60$ m.

The area S should be covered with crater ejecta of a thickness more than the minimal depth d of bright material to yield the observed brightening of the surface. The distance R_e (from the center of a crater of a radius R_{cr}) such that at $R < R_e$, the depth of ejecta is more than d can be derived from [8]:

$$R_e(R_{cr},d) = 0.289(R_b)^{0.2}(R_{cr}^3/d)^{0.4},$$

where $R_b \approx 0.3\sigma/\rho_r g$ is the minimum path of ejecta, $\sigma \approx 10^6$ dyn/cm^2 and $\rho_r \approx 1.5$ g/cm^3 are target strength and density, respectively, and $g = 167$ cm/s^2 is the lunar gravity. Note, that there are no ejecta at $R < R_{cr} + R_b$. Then the area S_c covered with craters or with ejecta of a thickness more than d is

$$S_c(R_{cr},d) = \pi[R_e(R_{cr},d)^2 - (R_{cr} + R_b)^2 + R_{cr}^2]N_{cr},$$

if $R_e(R_{cr},d) > R_{cr} + R_b$, and

$$S_c(R_{cr},d) = \pi R_{cr}^2 N_{cr}, \text{ if } R_e(R_{cr},d) < R_{cr} + R_b.$$

Here $N_{cr} = V/V_{cr}$ is the number of craters of the radius R_{cr} and volume $V_{cr} = \pi R_{cr}^3/4$ (paraboloid crater with depth to diameter ratio 1:4). $S_c(R_{cr},d)$, as a function of R_{cr}, has two branches. The "crater" branch that falls with increasing R_{cr} dominates at small R_{cr}; at larger R_{cr}, "ejecta" branch appear, with a maximum of height and position depending on the ejecta depth d. From equation $S_c(R_{cr},d) > 4S$ (the factor 4 takes crater or ejecta overlap into account) we obtain the possible radii of the craters to cover the area S at a given depth d. For ejecta depths large enough, the equation has only "crater" solution, i. e., at a given total mass the meteoroid shower, only a cover by small craters produced by dust particles is possible. With decreasing d we obtain the interval of crater radii to cover the surface with ejecta (Fig 1).

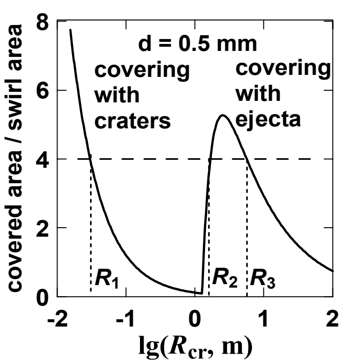

Fig.1

For $d = 0.5$ mm, this yields either R_{cr} from $R_2 = 1.7$ m to $R_3 = 5.6$ m, (so that $3.3 \cdot 10^5 < N_{cr} < 1.2 \cdot 10^7$, the maximum ejecta distance R_e from 20 to 80 m, and the projectile diameters d_p from 12 to 42 cm) for covering with ejecta, or $R_{cr} \leq R_1 = 3$ cm, ($N_{cr} \geq 2.1 \cdot 10^{12}$, $d_p \leq 2.2$ mm) for covering with craters of depth $H_{cr} \approx R_{cr}/2 \leq 1.5$ cm. Obviously, only craters with $H_{cr} > 1$ cm and hence with $R_{cr} > 2$ cm are consistent with the assumption of plow depth $H = 1$ cm.

(3) Interparticle collisions in ejecta. If the length of the meteoroid swarm is about its projection (~100 km), the shower falls during $\tau_m \sim 10$ s. The time of the ejecta flight is of the same order: $\tau_e = \sqrt{2}\, v_e/g \sim 10\text{-}10^2$ s. This means that the ejecta of many craters are formed almost simultaneously and the regolith particle of the ejecta collide with each other. The collisions may produce two effects: particle crushing and formation of the curls, which are the most peculiar detail of the swirls.

Simple estimations show that the collisions really occur and are numerous. The average path between collisions of regolith particles ejected up to height h_e is $\lambda_c = h_e l/sH$, where s is the volume fraction of particles in the regolith and $h_e = v_e^2/2g$. Time between collisions is $\tau_c = \lambda_c/v_e = v_e l/2gsH$. For the number of collision per particle flight obtain $\tau_e/\tau_c = 2^{3/2}sH/l$, which, at $H = 1$ cm, $s = 0.5$ and $l = 100$ μm yields $\tau_e/\tau_c = 141$. For most typical $v_e \sim 10^3$ cm/s, h_e is from tens to hundreds of meters and λ_c is from tens centimeters to tens meters. The estimation of τ_e/τ_c is independent of height and velocity, i. e. valid for all heights and free paths of the ejected particles. So large τ_e/τ_c means that the ejecta form a "gas" of regolith particles characterized by density, mean free path, etc. The kinematic viscosity of such a gas is $\nu = v_e\lambda_c/3$, and the effective Reynolds number for a jet of ejecta of a velocity v_j and width w penetrating into a cloud of colliding particles is $\mathrm{Re} \sim v_j w/\nu \sim (v_j/v_e)(w/\lambda_c)$. This means that penetration of a jet of high velocity and large width into low-height part of the ejecta cloud ($\mathrm{Re} \sim 10^5$) may be accompanied by the formation of swirl structures.

Conclusion: Our calculations have shown that the effects of coma gas in cometary encounter with the Moon are negligible as compared to those of comet nucleus explosure. The most probable mechanism responsible for swirl formation and the optical properties of swirls is interaction of cometary debris with lunar regolith. Rareness of swirls may be due to rareness of comet nucleus thermal decay close enough to the Moon to produce dense meteoroid swarm. Therefore swirls are expected to be more numerous on Mercury due to more frequent cometary decays and more dense clouds of cometary debris in the vicinity of the Sun.

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